Bi-directional Effects on the Response of an Isolated Bridge

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Abstract— **The seismic design of bridge structure is influenced by the bi-directional excitation phenomenon. The bi-directional effects have been ignored in most of the past studies. The calculation of maximum isolator displacements (as per the equation prescribed by AASHTO) also ignores the bi-directional effects of ground motion. In the formulation, the coupled behaviour of the isolation systems has also been ignored. However, these effects can play significant role in the seismic response of the bridge. In the present paper, the effet of bi-directional excitation on the seismic response of a continuous bridge has been studied, considering the interaction effects in Bearings and piers. The study has also been performed considering the effect of orientation of the major component of ground motion with respect to the axis of the bridge. Comparison of the responses obtained from the Nonlinear (Static) Pushover analysis and Nonlinear Dynamic Time History analysis have also been performed. It has been found that the bi-directional excitation has resulted in significantly higher response especially in case of PF system, where the uni-directional analysis yield significantly underestimated results.**

Index Terms—**seismic, bridge, bi-directional, isolator, pushover, time history**

I. Introduction

The present methods for design of bridge structure are mainly focused on determining the maximum response in a particular direction of the structure. Since the erthquake motion is randomly varied, the critical combination of the responses due to directional effect may not coincide with the maximum value of the uni-directional responses. There had been several studies in the past investigating the usefulness of isolation devices, but most of them had focused on uni-directional responses while the effect of bi-directional excitation on the seismic response of isolated bridges had been ignored.

The AASHTO (1996, 1999) [1, 2] equation for calculating maximum Isolator displacements also ignores the bi-directional effects of ground motion. Some studies are available in literature [3, 4, 5] suggested that bi-axial interaction in case of Isolation Bearings can have significant effect on the seismic response. Therefore, the effect of bi-axial interaction and efficacy of the prevailing design practice, considering a single component of earthquake motion along the principle directions of bridge, need to be investigated. The need for study of coupled behaviour of isolation bearings under bi-directional motions has also been identified by many researchers.

This paper presents the seismic response of the bridge under uni-directional and bi-directional ground excitations, incorporating the interaction phenomenon in Isolation Bearings and piers. Five types of Isolation Bearings have been considered in the study. A three span continuous bridge has been considered for the study purpose. A site specific design response spectrum, with a set of five compatible acceleration time histories, has been used for study of the seismic response. The applicability of the Nonlinear Static Pushover analysis in determining the seismic response of the isolated bridge has been investigated by comparing the responses obtained using Nonlinear Dynamic Time History Analysis. The response of the bridge, with different orientations of the major component of ground motion with respect to the axis of the bridge, has also been determined and compared with uni-directional responses

II. Bearing Types Considered

The response of the continuous bridge with the following types of Isolation Bearings has been studied:

- High Damping Rubber Bearing (HDR),
- Lead Rubber Bearing (LRB),
- Pure Friction System (PF),
- Electricite de France System (EDF), and
- Friction Pendulum System (FPS).

III. Bridge Considered For The Study

An existing three span railway bridge, situated in Northern India, has been considered. The site of the bridge falls in Seismic Zone IV of Indian seismic zoning [6]. It is a continuous prestressed concrete box girder bridge. The bridge has a total length of 192 meter with the main span of 80 meter and two end spans of 56 meter, each (Fig. 1). The height of the piers is 36.355 meter. The pier section is hollow circular with an external diameter of 6.5 meter and thickness of 0.5 meter. The piers are resting on rocky strata.

IV. Modelling

The bridge structure has been modeled (Fig. 2) using the software SAP2000 Nonlinear. The superstructure and the piers have been modeled using beam elements with mass lumped

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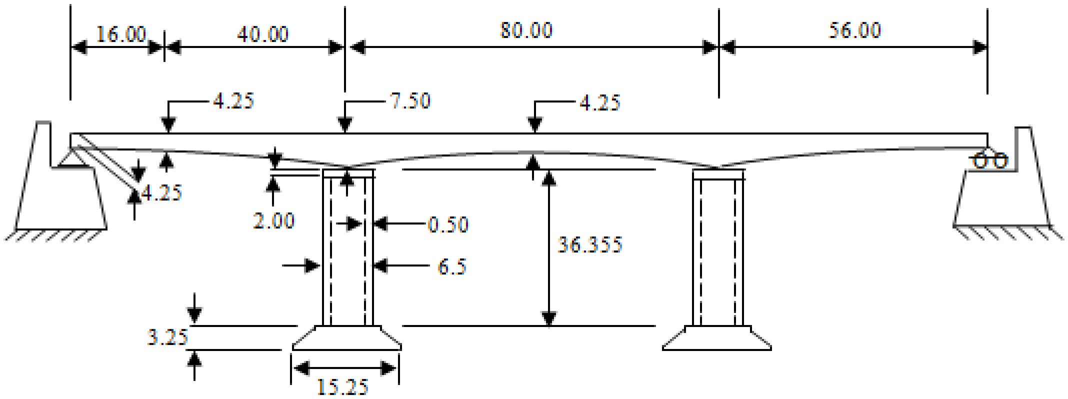

Figure 1. Three span continuous bridge

at discrete points. Since the piers are resting on rock, these have been modeled as fixed at base. The abutments have been assumed to be rigid.

The Isolation Bearings have been modeled as link elements. To model the spatial placement of bearings across the section, horizontal cross rigid links have been used. Nonlinearity has been considered in the Bearings and piers. Plastic hinges at bottom and top of pier elements have been assigned to model the nonlinear properties of the piers. Normally, the major component of axial load in the piers is due to gravity loads. In case of seismic loading, some additional axial load may come due to frame effect.

In the present study, the bridge has no frame action in the transverse direction. In the longitudinal direction, some frame action exists, but, it has been observed that the axial load generated due to earthquake is negligible. Therefore, the effect of seismic axial forces on yielding and ductility of piers has been ignored, and bi-linear moment-rotation relationships based on the gravity load component of axial force have been used to model the nonlinear behaviour of piers. To consider the bi-axial interaction effect in piers, moment-moment interaction curve for a constant axial load has been determined. For analysis of bridges under bi-directional excitation, coupled plasticity behaviour of Isolation Bearings has been assigned in the link elements. The *P-Ä* effects have also been considered in the study.

A. *Coupled Plasticity Behaviour of Isolation Bearings*

The coupled behaviour of the Isolation Bearings has been considered according to the hysteretic model proposed by Wen [7], and Park, Wen and Ang. [8], and recommended for base-isolation analysis by Nagarajaiah, Reinforn and Constantinou [9].

The coupled force-deformation relationship is given by,

$$F_1 = R_1 K_{e1} u_1 + (1 - R_1) F_{y1} z_1 \quad (1)$$

$$F_2 = R_2 K_{e2} u_2 + (1 - R_2) F_{y2} z_2 \quad (2)$$

where, K_{e1} and K_{e2} are the elastic stiffnesses in twoorthogonal horizontal directions, F_{y1} and F_{y2} are the yield forces and u_1 and u_2 are displacements in the two directions, R_1 and R_2 are the ratios of post-yield stiffnesses to elastic stiffnesses and

z_1 and z_2 are internal hysteretic variables and these variables have a range of ± 1, with the yield surface is represented by $\sqrt{z_1^2 + z_2^2} = 1$.

For the PF system, $R_1 = R_2 = 0$ and the force-deformation relationships are given by,

$$F_1 = \mu W z_1 \quad (3)$$

$$F_2 = \mu W z_2 \quad (4)$$

where, μ = friction coefficient and

W= weight of superstructure on the PF system.

V. Analysis

The bridge structure with different types of Bearings has been analysed for seismic loadings. Both Nonlinear Static (Pushover) Analysis, as well as, Nonlinear

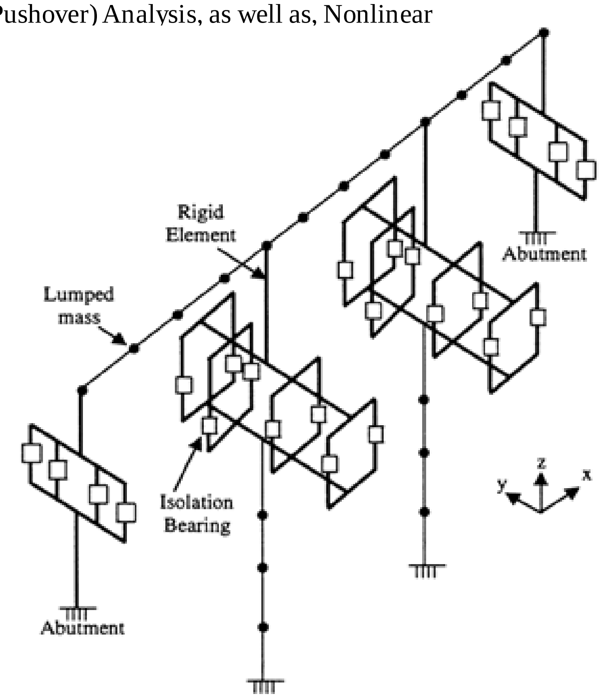

Figure 2. 3-D model of the continuous bridge with isolation bearings

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Dynamic Analysis (NLTHA) have been performed and the results have been compared.

The accuracy of the Pushover Analysis depends on the selection of a lateral load pattern representative of thedistribution of nodal accelerations during earthquake, and a control node, where the displacements are monitored and considered as representative of the displacements of the whole structure. FEMA-356 [10] has provided detailed guidelines for selection of loading pattern and control node for buildings. Such guidelines are not available for bridges. The bridges have a significant difference as compared to buildings. The buildings generally have floor slabs which are rigid in horizontal plane, imposing a geometric pattern of lateral load and displacement on various lateral load resisting elements. On the other hand, the bridge deck, due to its long span, cannot be considered rigid against displacement in the transverse direction. However, the rigidity of the bridge deck is quite high in longitudinal direction. In the present study, the mid-span node along the central axis of the bridge deck has been considered as the control node in pushover analysis.

In SAP2000 Nonlinear software, four variants of Nonlinear Static (Push-over) Analysis procedures are available: (i) ATC-40 Capacity Spectrum Method (CSM) [11], (ii) FEMA-273 [12] / FEMA-356 Displacement Coefficient Method (DCM), (iii) FEMA-440 Equivalent Linearization Method (ELM) [13] and FEMA-440 Displacement Modification Method (DCM). The last two methods have been developed as improvement of the first two methods, respectively (FEMA-440). The CSM is similar to the Equivalent Linearization Method commonly used for design of Isolation Systems [14] except that, it considers the deformations in the components of structures other than Bearings also. In FEMA-440, CSM has been improved by developing expressions for optimal equivalent linear parameters-Effective damping and effective period. A comparison of the results obtained from the different Pushover Analysis Methods with those obtained from the NLTHA has been presented earlier in a companion paper. It has been observed that the ELM yields satisfactory results in case of yielding (Elastomeric) type Isolation Systems, but

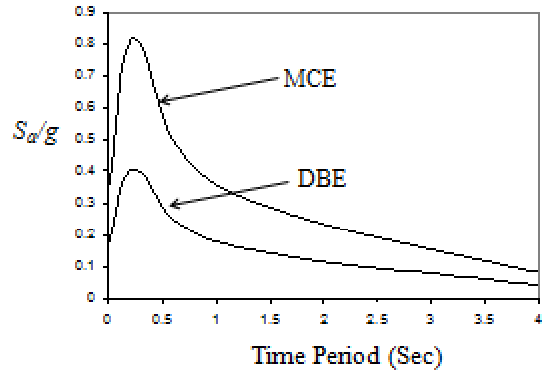

Figure 3. Site specific design response spectra for 5% damping

in case of friction-based systems, the expressions of FEMA-440 are not strictly valid, as those have been derived in terms of the ductility of the system. In case of friction-based Isolation Systems, the ATC-40 CSM has been observed to yield better results. Further, in case of PF Isolation System, the damping mechanism is based on Coulomb friction. For this system, the damping in the CSM has been modified using the expressions suggested by Makris and Chang (1998) [15].

VI. Seismic Loading

Site specific design response spectra are available (Fig. 3) for the bridge site for the Maximum Considered Earthquake (MCE). In case of seismic loading, five ground acceleration time histories, recorded for different earthquakes, world over, for different source and site conditions have been scaled in frequency domain, preserving their phase information [16], to make them compatible with the design response spectra. The recorded earthquakes (Fig. 4) considered are: (1) Elcentro (1940), (2) Kobe (1995), (3) Northridge (1994), (4) Loma Prieta (1989), and (5) San Fernando (1971).

VII. Parametric Study

To study the effect of orientation of ground motion with respect to the bridge axis, the displacement envelopes of the

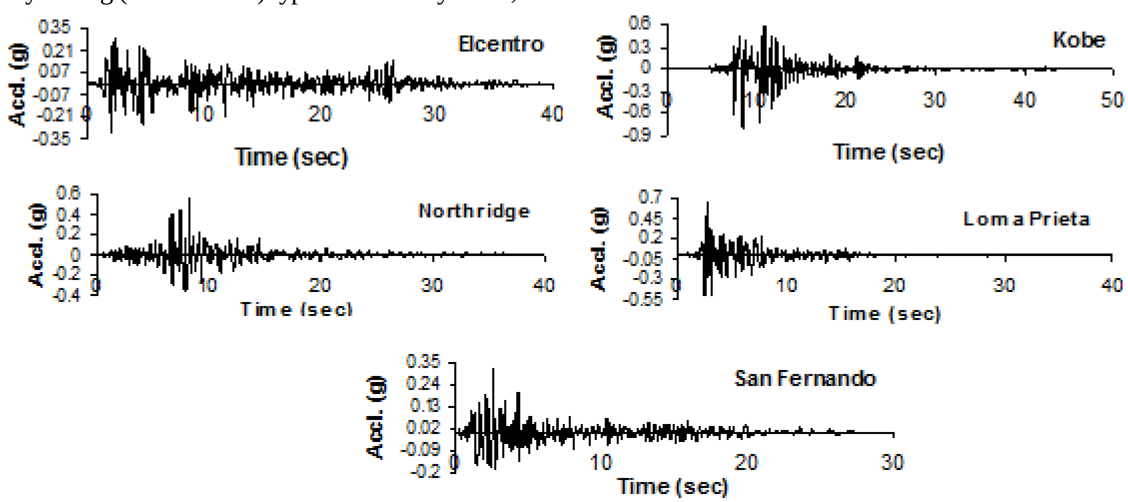

Figure 4. Ground motion time histories considered for the study

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bridge have been obtained from the Nonlinear Static (Pushover) Analysis, as well as uni-directional Time History Analysis.

The loads have been considered at 20 different angles. The results of Pushover Analysis have been compared with those obtained from Nonlinear Time History Analysis (NLTHA). For this purpose, the ensemble of five unidirectional time histories, compatible to MCE response spectrum, have been considered and the average, as well as, maximum of the peak responses obtained using these time histories have been used to determine the response envelopes.

Sets of two scaled accelerograms representing bi-directional ground motion (in two orthogonal horizontal directions) have been applied at different orientations with respect to the bridge axis. The major component of the bi-directional ground motion pair is made compatible with 100% MCE design response spectrum and the other component is compatible with 85% of the MCE design response spectrum. The trace of the bridge response has been plotted and compared with the response envelopes obtained from Pushover Analysis and uni-directional NLTHA.

A. Directional and Bi-Directional Effects

Fig.5 shows the envelopes of the bridge response under uni-directional seismic loading applied at zero degree angles w.r.t the bridge axis for the HDR bearings. The similar types of envelopes have been plotted for 45^0 directions also, for other types of bearings also. The envelopes have been plotted for the deck displacement at the mid-span node on the central axis of the bridge, obtained using the Pushover Analysis and NLTHA. The bi-directional coupling effect as described in section IV.A has been considered. In case of NLTHA, envelopes for both maximum and average peak response obtained for the five time histories have been plotted.

It can be observed that the response envelopes are close to elliptical with major axis in the transverse direction, as the bridge deck has flexibility in transverse direction. The effect of transverse flexibility is more pronounced in case of dynamic analysis, because in case of static analysis, a constant acceleration in the transverse direction has been applied throughout the length of the deck. It can be observed that the Pushover Analysis estimates the deck displacements

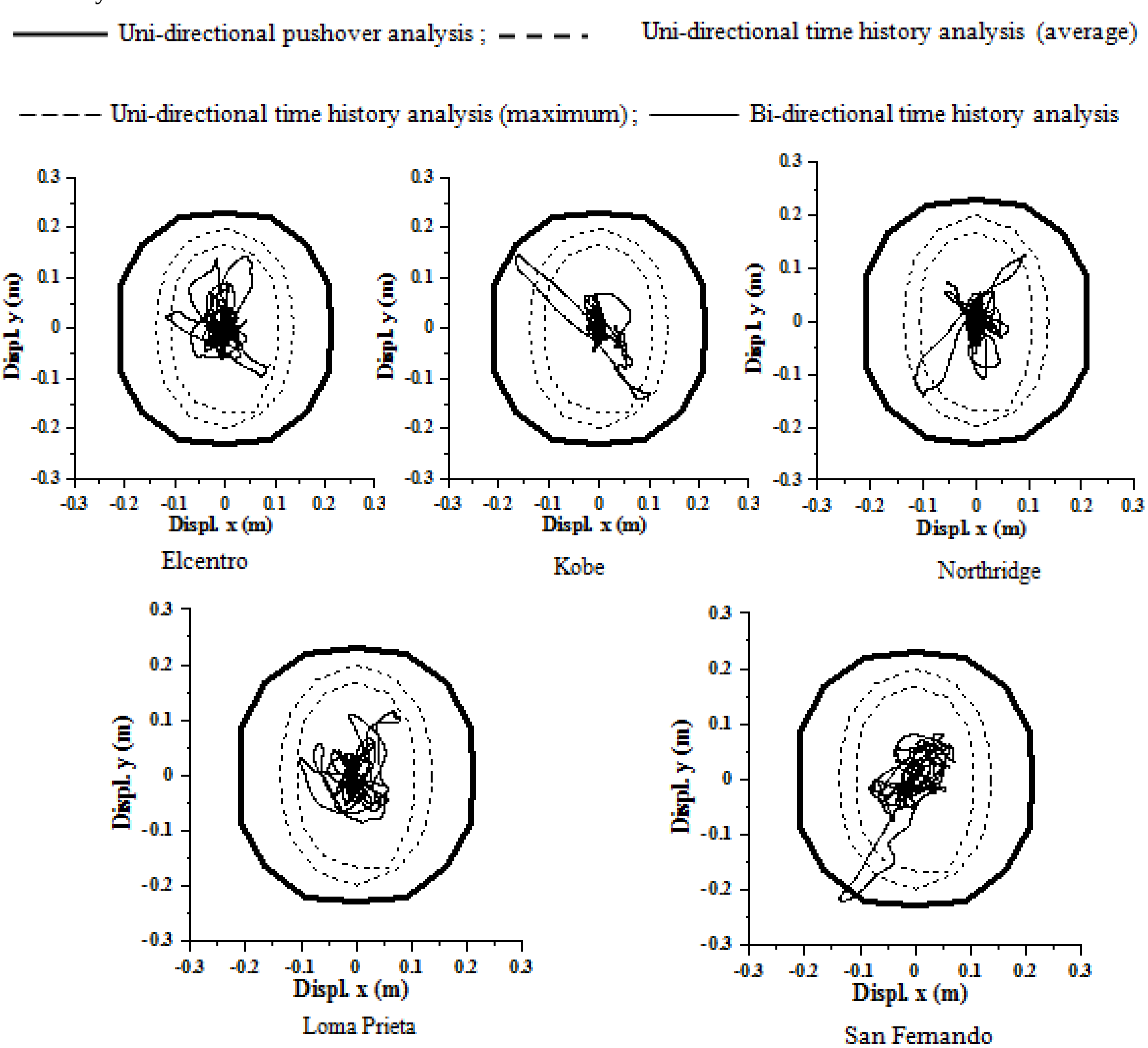

Figure 5. Displ. of the bridge with HDR bearings under unidirectional and bi-directional ground motions (major component oriented along the bridge axis)

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close to those obtained from the NLTHA, further the estimates from the Pushover Analysis are conservative in case of elastomeric systems but in case of friction-based systems the Pushover Analysis estimates are lower than the NLTHA results in the transverse direction. This indicates the need to develop better estimates of equivalent damping in case of friction-based systems.

The difference between the maximum and average response envelopes for the uni-directional NLTHA has been observed to be small in case of all the Bearings except the PF system, where the difference between maximum and average peak responses for the five time histories, considered in the study, are quite significant in the transverse direction of the bridge.The Fig.5 also shows the traces of the deck displacement under bi-directional excitation.

The displacement traces are shown in the Figures for 0^0 degree orientations of the major component of the time history pairs, w.r.t the bridge axis. The analysis was performed for other directions (45^0) also, and similar results were obtained, which are not shown. It can be observed that the bi-directional excitation has resulted in significantly higher response, as compared to the maximum response envelope obtained from the uni-directional NLTHA. The effect is maximum in case of PF system, where the uni-directional analysis yield significantly (62%) underestimated results.

Conclusions

In the present study, the effect of bi-directional ground motion on the seismic response of a three span continuous bridge, isolated with different types of bearings, has been studied. The coupled plasticity behaviour of the isolation bearings as well as the interaction phenomenon of the piers has also been considered in the study. The applicability of the pushover analysis in determining the seismic response of the isolated bridge has been investigated. As compared to the maximum response envelope obtained from the uni-directional NLTHA, the bi-directional interaction of ground motion components has increased the response of the bridge by a considerable amount with the maximum effect in case of PF system, where the uni-directional analysis yield significantly (62%) underestimated results. It has also been observed that in case of elastomeric-based isolation systems, Pushover Analysis estimates are conservative, but in case of friction-based isolation systems, the Pushover Analysis estimates are lower than the NLTHA results in the transverse direction.

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